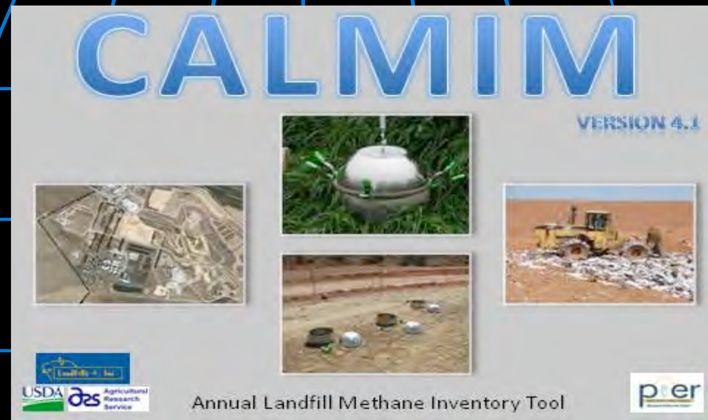
Agenda

- Guido Franco, CEC: Introduction to PIER research project "California landfill methane inventory model (CALMIM) for improved annual estimates of emissions from California landfills."
- Watson Gin, Calrecycles: CalRecycle's perspective about the landfill research project.
- Jean Bogner, Landfills +, Inc. and UIC: (a) overview of project and CALMIM; (b) field data & overview of supporting laboratory studies.
- Kurt Spokas, USDA/ARS: (c) detailed model description;
  (d) field validation of CALMIM.
- All: questions & discussion



CAlifornia Landfill Methane Inventory Model:

An Improved Field-Validated Inventory Methodology for Landfill CH_4 Emissions in California

Project participants:
Jean Bogner, Landfills +, Inc. and University of Illinois Chicago IL
Kurt Spokas, USDA-ARS, St. Paul MN
Jeffrey Chanton, Florida State University Tallahassee FL

California Energy Commission
Sacramento, CA - May 18, 2010

Overview of Project:

Goal: develop an improved GHG inventory methodology
for site-specific landfill methane (CH_4) emissions in California,
based on a field-validated emissions model
inclusive of seasonal methane oxidation

Schedule, Funding, Cooperation:

3 year project (2007-2010) funded by the
California Energy Commission PIER Program
(Public Interest Energy Research)
in cooperation with
Calrecycles & the California
Air Resource Board (ARB)

Project Participants:

J. Bogner, P.I., Landfills +, Inc. and University of Illinois Chicago, IL
K. Spokas, U.S. Dept. of Agriculture-ARS, St. Paul, MN
J. Chanton, Florida State University, Tallahassee, FL

Field Validation Sites (2 years):

Scholl Canyon Landfill (Los Angeles County Sanitation Districts)
Marina Landfill (Monterey Regional Waste Management District)

- What is CALMIM?

- Why did this project develop a new site-specific GHG inventory methodology for landfill methane?

- What did the field and laboratory validation program include?

A primary consideration:

Balancing science-based methods
with an appropriate level of detail
for an annual, regional GHG inventory...

CALMIM: freely available JAVA-based

CAlifornia Landfill Methane Inventory Model

(1) Site Location, Cover Materials/Area, and Gas Recovery Information (interactive template)

(2) Annual Meteorological Model:
air temperature, precipitation, solar radiation, evaporation

(3) Soil Microclimate Model:
temperature and moisture (1D)

(4) CH_4 Emission/Oxidation Model
(1D diffusion)

Annual Methane Emission Estimate for Site: for each cover & site total

Field Validation and Supporting Laboratory Studies

New GHG Inventory Methodology based on:

- Site-specific distribution of daily, intermediate, and final cover soils (user-friendly JAVA template) for any combination of layered cover materials up to 100 in thick (I)

- Site-specific climatic modeling with USDA globally-validated methods based on regional climatic databases and soil microclimate (temperature and moisture) variability over an annual cycle (II & III)

- Modeling of "net" emissions inclusive of engineered gas recovery & seasonal methane oxidation using a 1-D model with 10 min. time steps and 1 in depth increments for each cover (IV)

Field Validation and Supporting Laboratory Studies:

- Field validation over 2 annual cycles at:
coastal Marina LF (Monterey County)
semi-arid Scholl Canyon LF (LA County)

- Supporting laboratory studies for methane oxidation over wide range of temperature and soil moisture conditions

Why California? Why now? ....develop a new GHG inventory method for landfill methane emissions

Note: 2006 California landfill methane emissions estimated at : 6.3 Mt CO_2 eq (1.3% of gross emissions; 1.6 % of net emissions "by scoping category").

- Improved method for California statewide GHG inventory:
  - Research review recommending improved methods (Farrell et al., 2005).
  - Need for better numbers for state inventory, state legislative mandates (AB32), and evolving Federal legislation...
- Time is right...Advances in scientific understanding based on the research literature (field & laboratory studies in several countries over the last 15 years) have led to:

✓ Improved understanding of landfill methane emissions & oxidation processes & rates.

✓ Realization that the theoretical landfill methane <u>generation</u> models, which were developed to model commercial landfill methane <u>recovery</u> during the 1970's ---> not a good predictor for emissions, esp. where high rates of recovery (>90% of waste in place in California under active gas extraction).

Current inventory methodologies reference the IPCC National GHG Inventory Guidelines...

Latest version: IPCC, 2006: *IPCC Guidelines for National Greenhouse Gas Inventories.* IPCC/IGES, Hayama, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.html.

For landfill methane (CH_4):

Tier 1 & 2: ("First Order Decay")

Multicomponent first order kinetic model for methane generation based on annual landfilled waste, composition, methane generation potential (Lo) and kinetic constant (k).

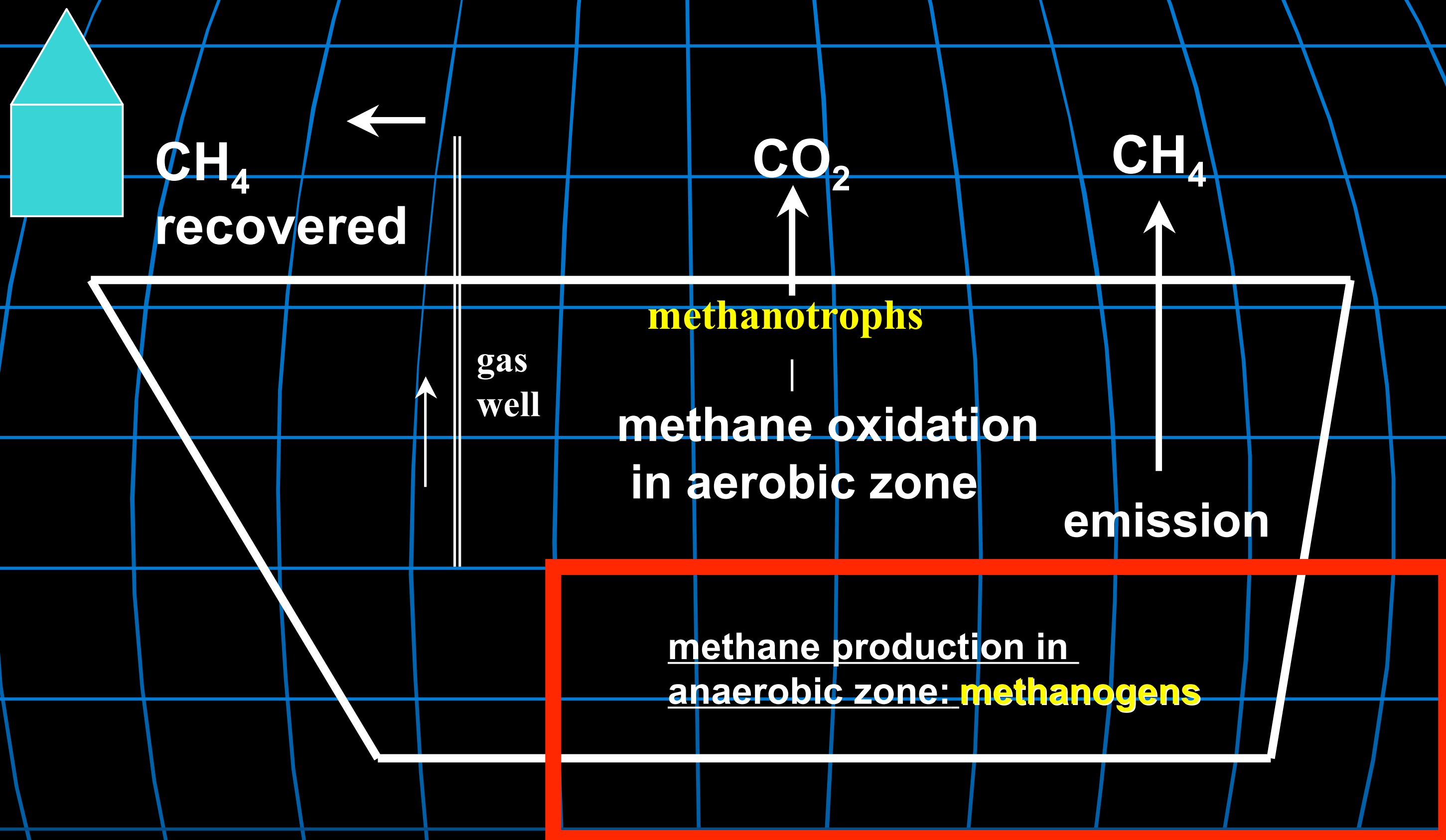
status quo

***Tier 1a*: FOD model based on waste composition.**
***Tier 1b*: FOD model based on type of disposal site.**

Tier 2: country-specific FOD model

Tier 3: validated country-specific methods which are of equal or higher quality

Our starting point for this project...using modeled methane generation as a source term:



Methane [CH_4] generated, *kg/day* =
Σ (CH_4 recovered +
CH_4 emitted + CH_4 oxidized +
CH_4 migrated + Δ CH_4 storage)

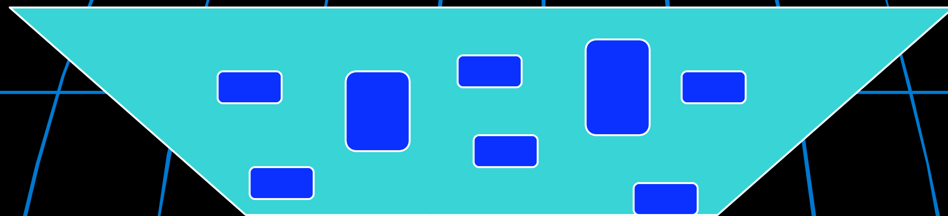
and improving the methane mass balance modeling...

However, we abandoned that approach due to fundamental issues with FOD method for emissions:

- Assumptions of approach regarding landfill CH_4 processes:
  - Assumes a well-mixed anaerobic digester.
  - Does not assume any cover materials.
  - Assumes a uniform 10% methane oxidation in cover materials.
- Never field-validated for emissions: originally site-specific FOD models developed to model gas recovery .
- Recent field data indicates method is not a good predictor for for site-specific emissions.

The FOD method was a reasonable starting point 15-20 years ago in the absence of field measurements of emissions, but today we can do better...

Questionable assumptions…



…landfills in a region function as well-mixed anaerobic digesters with methane generation dependent on one theoretical first order equation.

BUT (based on measured recovery), many sites deviate from "theoretical" generation.

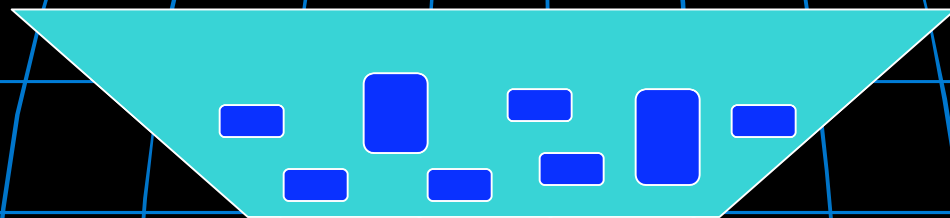
…"Measured" methane recovery subtracted from "theoretical" generation is a reasonable measure of emissions.

BUT it is important to consider the effect of engineered gas recovery and the variable effects of site-specific cover materials (daily, intermediate, final) to retard emissions

… 10% methane oxidation occurs in cover materials (based on Czepiel et al., 1996).

BUT recent literature indicates that methane oxidation rates are related to methane oxidation potential and seasonable variability (moisture, temperature) in any given cover material.

Never field validated for emissions...



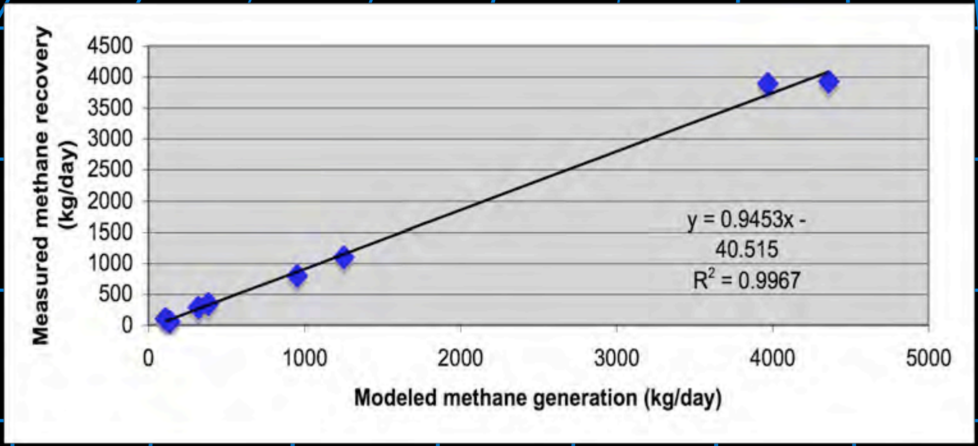
Field validation of IPCC multicomponent FOD model:

Dutch studies (Van Zanten and Scheepers, 1994) which compared measured gas recovery to modeled generation using zero order, first order, and second order models based on data from full-scale Dutch landfills.

Field validation of LandGEM (single component FOD model):

U.S. studies which compared measured gas recovery to modeled generation (Peer et al., 1993).

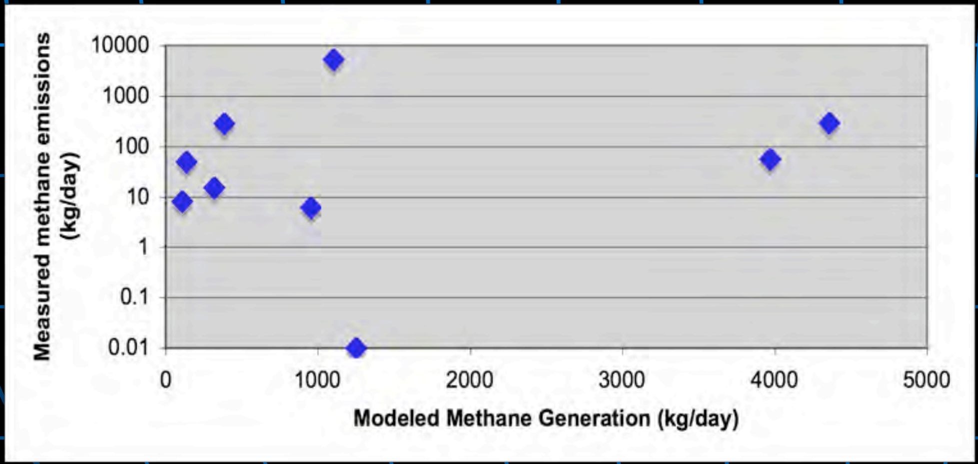
Modeled landfill methane generation with detailed input data and local experience can be a good predictor for recovery…



French field scale study 2002-2005
Methane mass balance at 7 cells at 3 sites (Spokas et al., 2006):

Methane [CH_4] generated, *kg/day* = Σ (CH_4 recovered + CH_4 emitted + CH_4 oxidized + CH_4 migrated + Δ CH_4 storage)

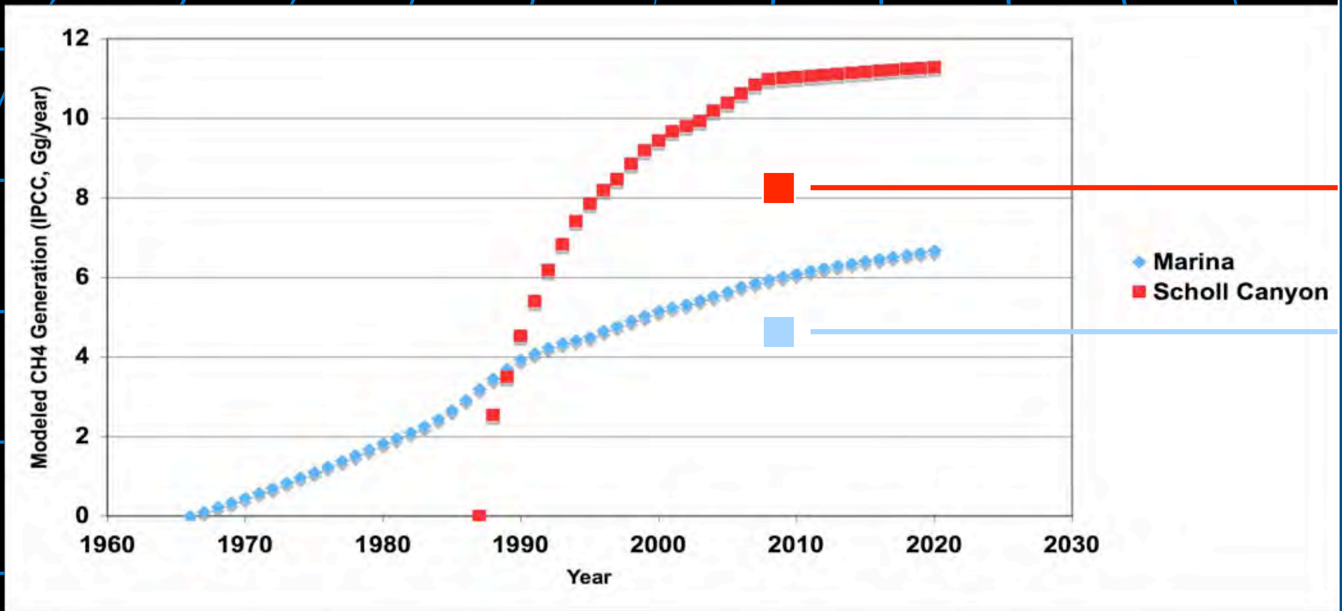
but not for emissions…

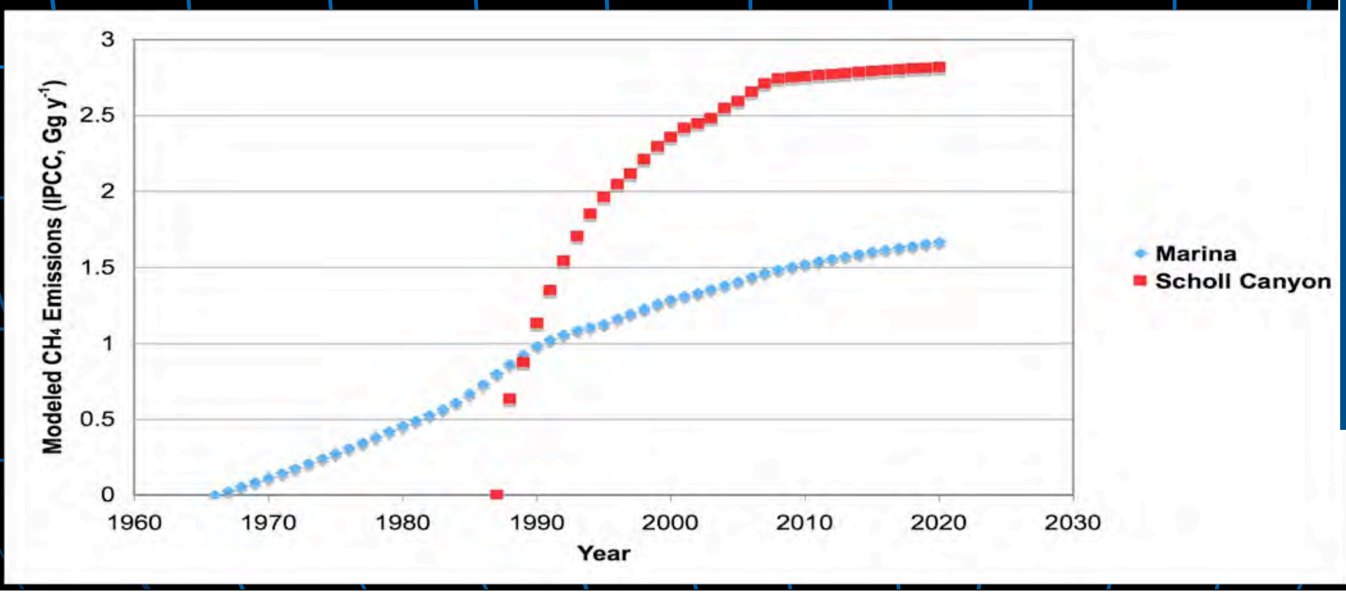


Sites and Cells:

Montreuil-sur-Barse (NE France near Troyes)
Final clay cover with LFG recovery
Final GCL cover with LFG recovery
Lapouyade (SW France near Bordeaux)
Final clay cover with LFG recovery: summer, winter
Thin temporary clay cover with LFG recovery: summer, winter
Thin temporary clay cover without LFG recovery: summer
Grand' Landes (W France near Nantes)
Final clay cover with LFG recovery
Final geomembrane cover with horizontal LFG recovery

Using IPCC Tier 1 multicomponent methodology with
Recovery = 0.75 * Generation and
Emissions = 0.90 * [Generation - Recovery]





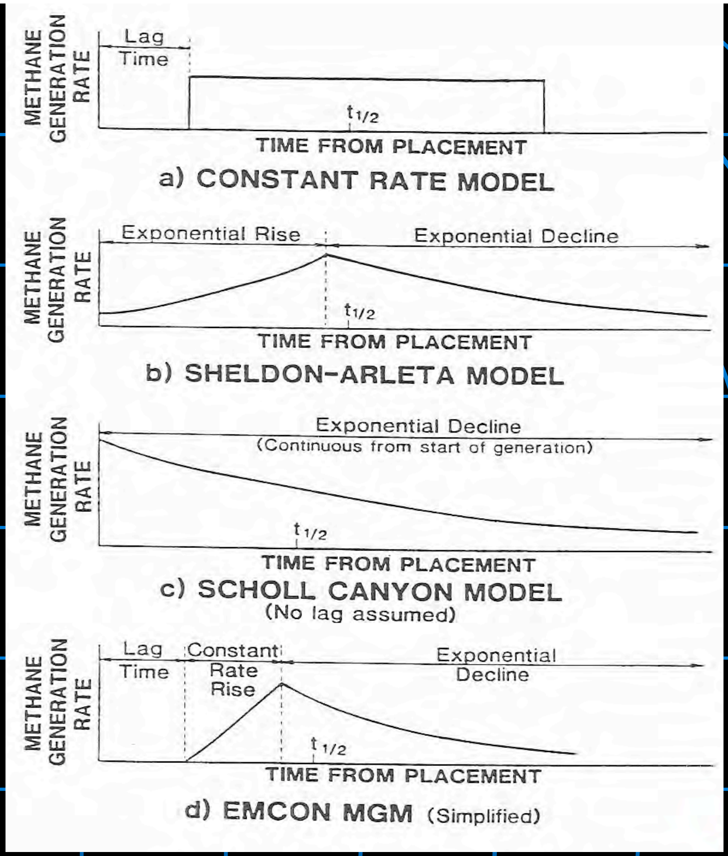
But if compare modeled recovery to actual 2009 methane recovery:

28.4 Gg: Scholl Canyon

8.6 Gg: Marina

Numbers do not match...

Original FOD models were
all site-specific...



$$Q_T = \sum_{i=1}^{n} 2kL_oM_ie^{-kt_i}$$

Q_T = total generation rate from a landfill, mass/time
k = landfill gas generation rate constant, time^{-1}
L_o = methane generation potential, volume/mass of waste
t_I = age of the i^{th} section of waste, time
M_I = mass of wet waste, placed at time i
n = total time period of waste placement

Going back to the IPCC National GHG Inventory Guidelines...

Latest version: IPCC, 2006: *IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC/IGES, Hayama, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.html.

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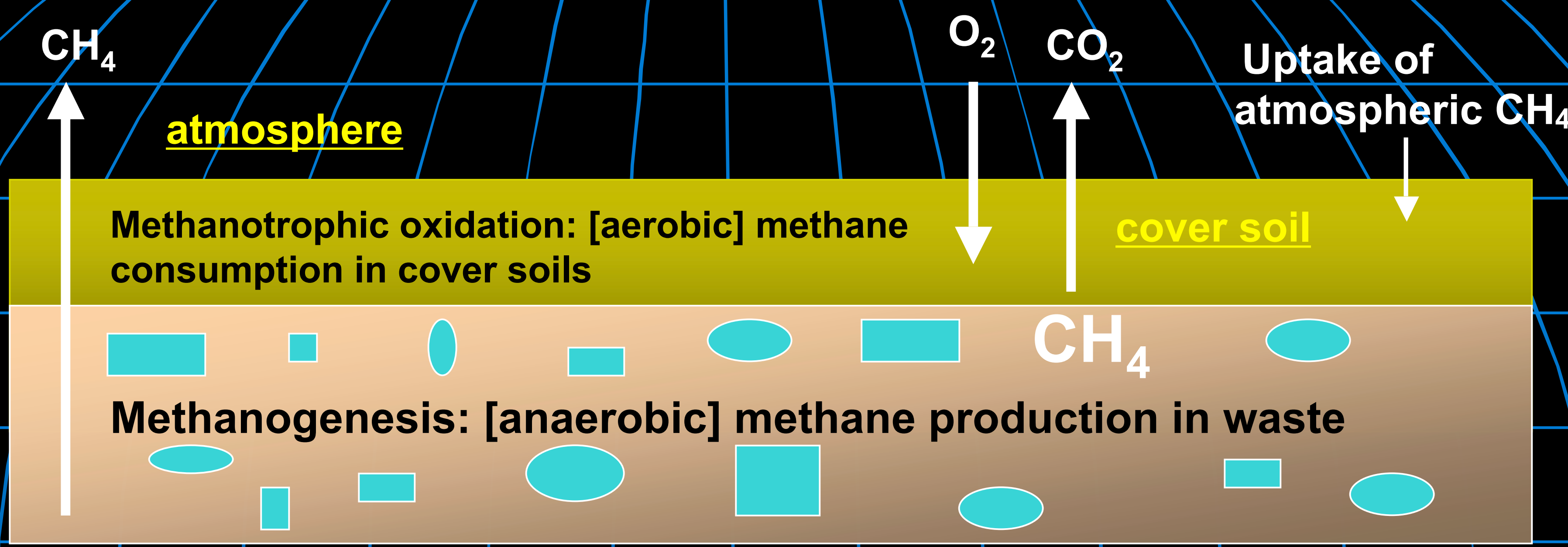
this project → **Tier 3: validated country-specific methods which are of equal or higher quality**

...moving entirely away from FOD method based on generation to an EMISSIONS-BASED approach



What are the most important controls on emissions?

LFG Recovery: reduces CH_4 concentration in soil gas at base of cover materials, thus reducing diffusive flux.

Properties of cover materials: reduces emissions based on physical properties

Seasonal rates of methanotrophic oxidation in cover materials: can reduce emissions depending on seasonal oxidation capacity vs. flux rate

Why do emissions not depend on mass of waste & methane generation rate?

First, site w/o gas recovery:

Diffusional flux, J, mass/area/time = $(D_e)*(\partial C/\partial z)$

waste thickness = 15 m

waste mass = 1 Mg

CH_4 at base of cover = typically 40-60 % v/v

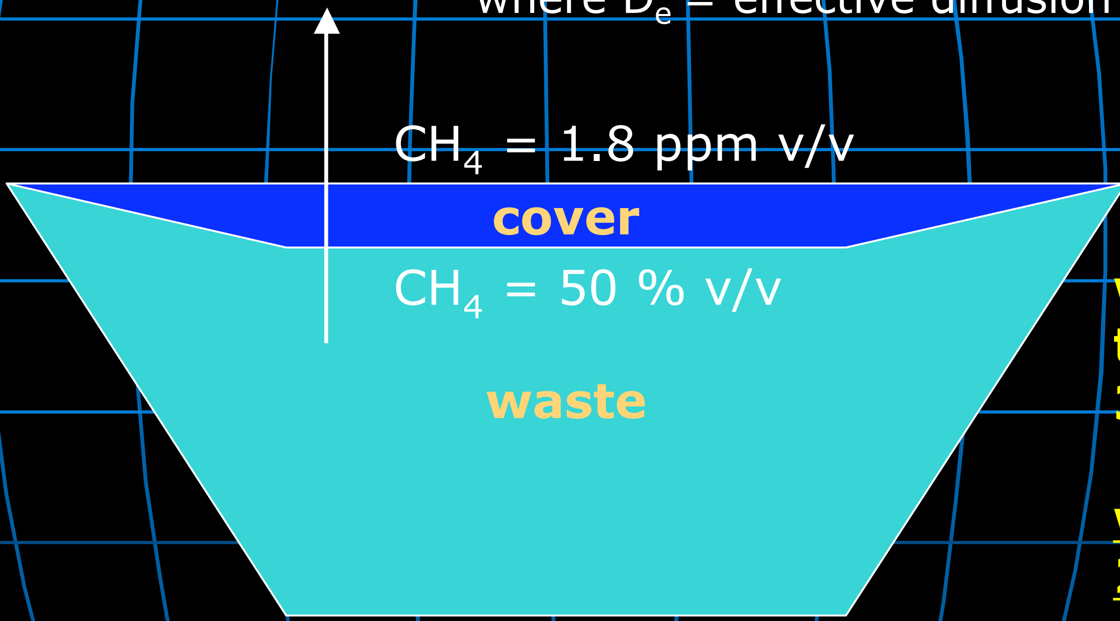
large (dc/dz) --> high emissions, typical of sites w/o engineered gas recovery

The same site w/o gas recovery:

If we double the waste mass,
the diffusional flux = <u>same</u>, dependent on
concentration gradient and cover properties...

Diffusional flux, J, mass/area/time = $(D_e)*(\partial C/\partial z)$

where D_e = effective diffusion coefficient



waste thickness = 30 m

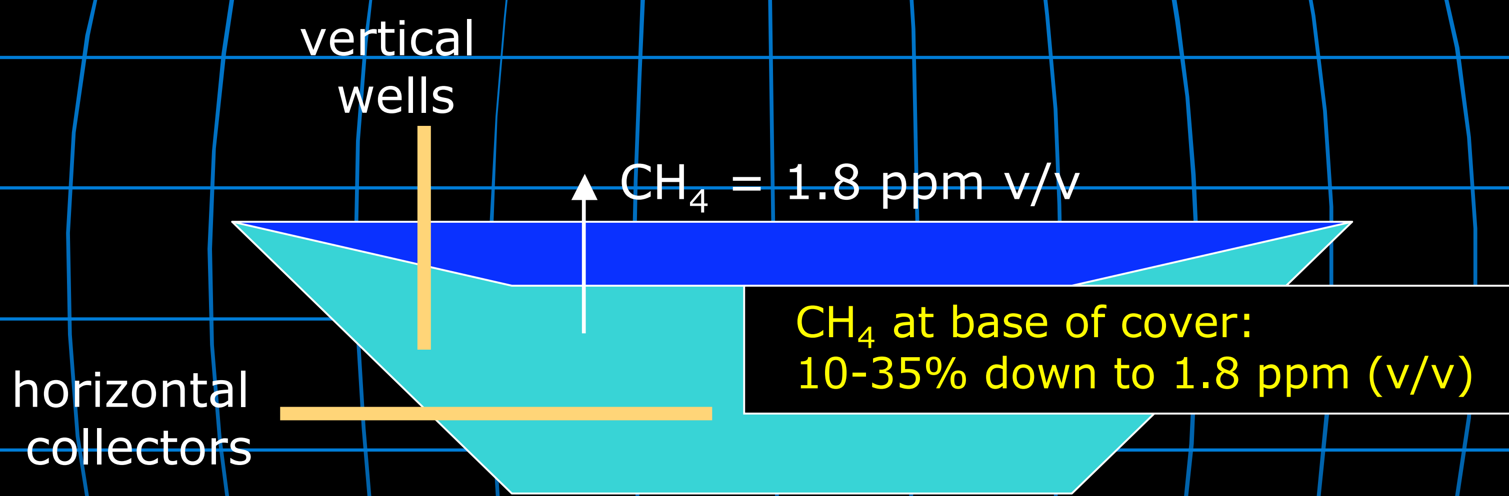
waste mass = 2 Mg

CH_4 at base of cover = 40-60 % v/v

Now, add gas recovery:

Diffusional flux, $J = (D_e)*(\partial C/\partial z)$

where D_e = effective diffusion coefficient



(dc/dz) reduced --> emissions reduced

maximum measured emissions (no gas recovery and minimal oxidation): >1000 g $m^{-2}d^{-1}$

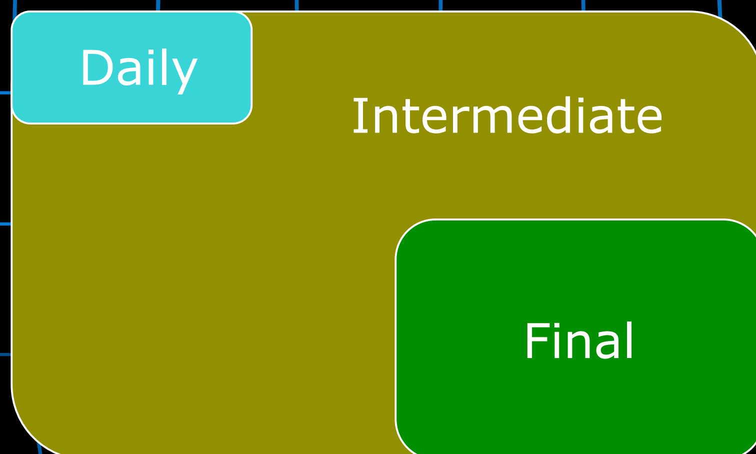
minimum measured emissions (effective gas recovery and effective oxidation): <0.0001 g m^{-2} d^{-1}

MODELING the most important controls on landfill methane emissions using CALMIM…

Engineered gas recovery (>90 % of waste in place in permitted CA landfills)

Properties of cover materials (& seasonal methane oxidation)

CALMIM framework…



Information required:

% of footprint with daily, intermediate, final cover
Properties of each cover material
% of each cover area with engineered gas recovery

Field Validation

• Process level studies of methane emission rates ($g\ CH_4\ m^{-2} day^{-1}$) using static closed chambers on fresh refuse & daily, intermediate, and final cover materials at Marina and Scholl Canyon (>850 fluxes)

• Stable carbon isotopic method of Chanton and Liptay (2000) for determination of fractional methane oxidation.

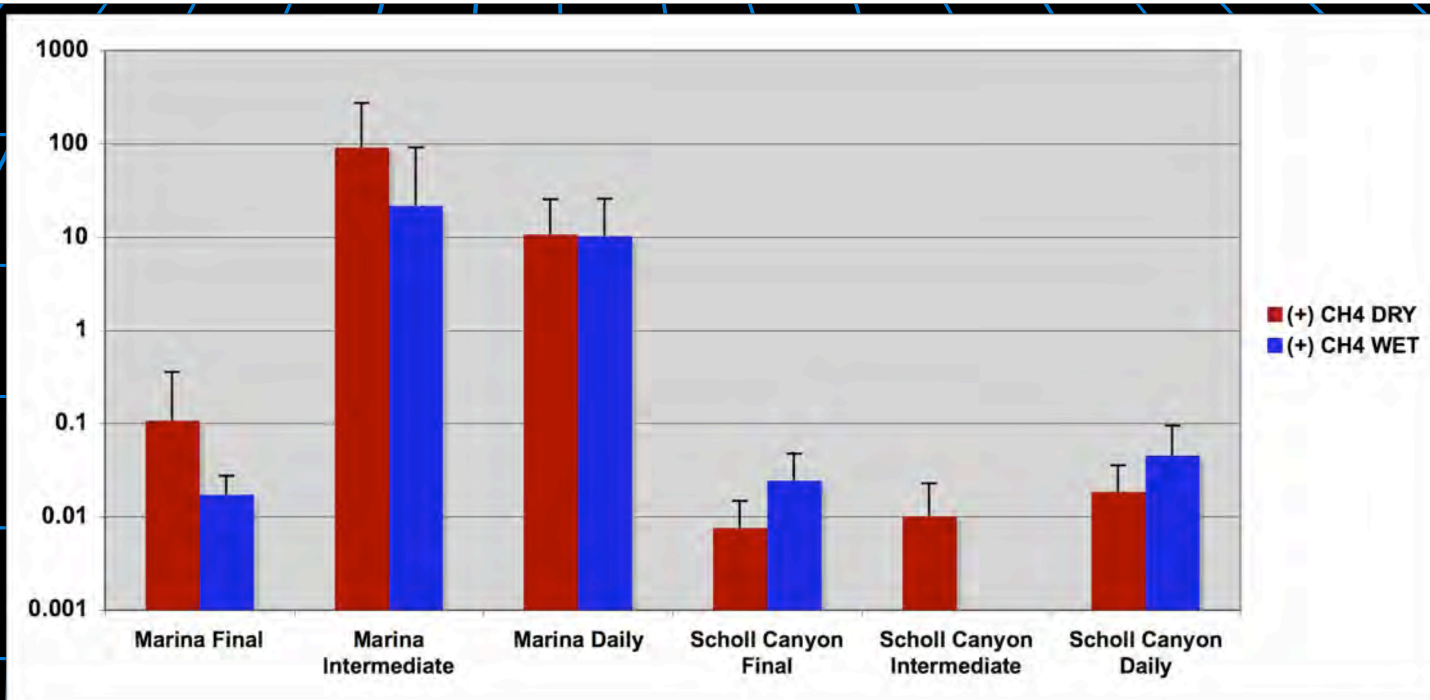
• Supporting data for each flux:

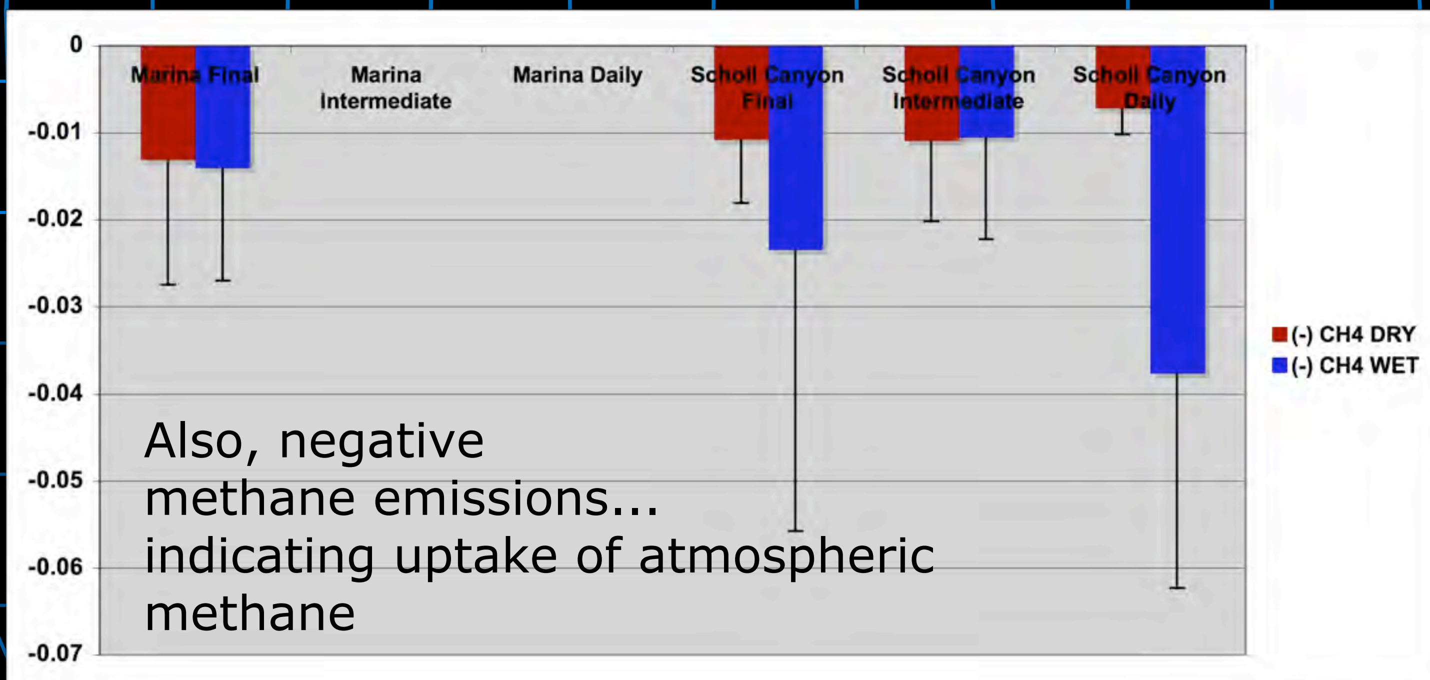
5 cm soil moisture (TDR), soil gas concentrations,
soil temperature (RTD), GPS location,
air temperature, continuous chamber temperatures,
and continuous water vapor (in chamber)

• Other supporting field studies/data:

continuous sub-surface CO_2 & pressure monitoring
Differential pressure in chamber
CO_2 & N_2O flux data

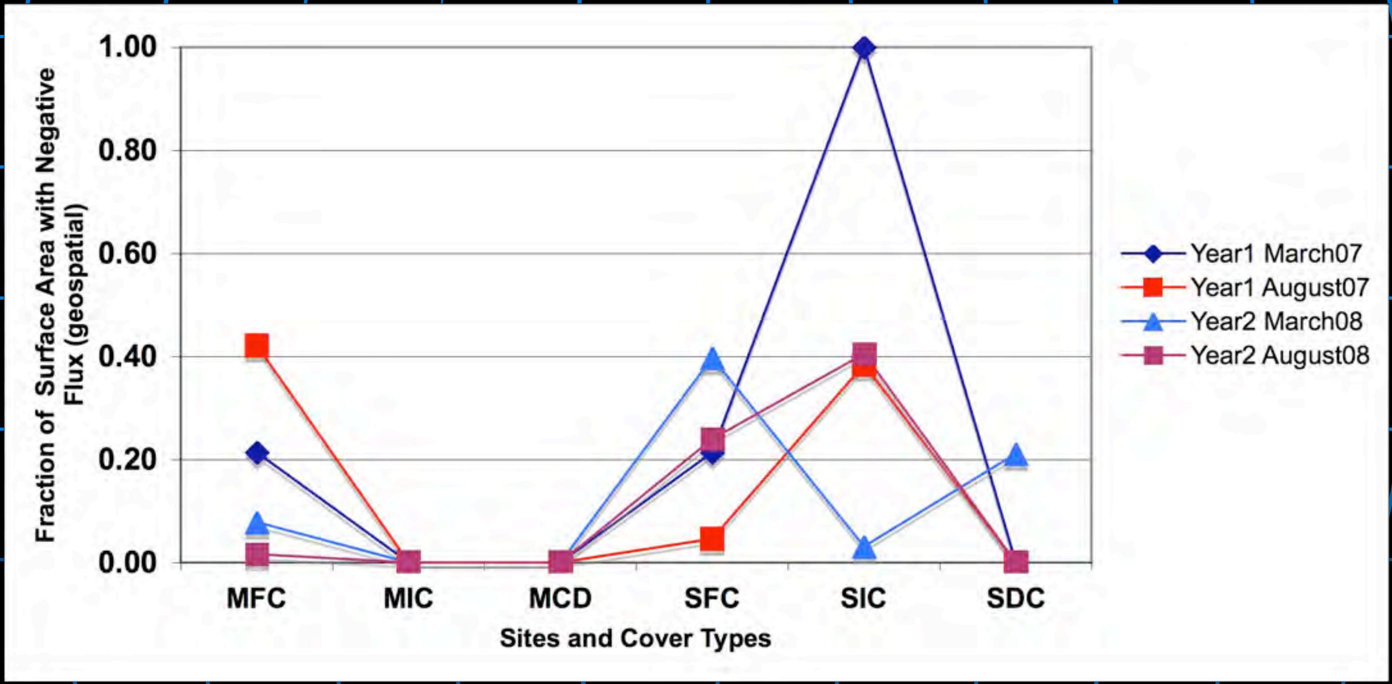
Measured methane emissions vary by about 4 orders of magnitude but for most cover materials (SDC, SIC, SFC, MFC) average < 0.1 $g\ m^{-2}\ d^{-1}$





Also, negative methane emissions... indicating uptake of atmospheric methane

Using a geostatistical method (IDW), the fraction of surface area of each cover type with negative emissions (uptake of atmospheric methane):



Field data: CH_4 Oxidation

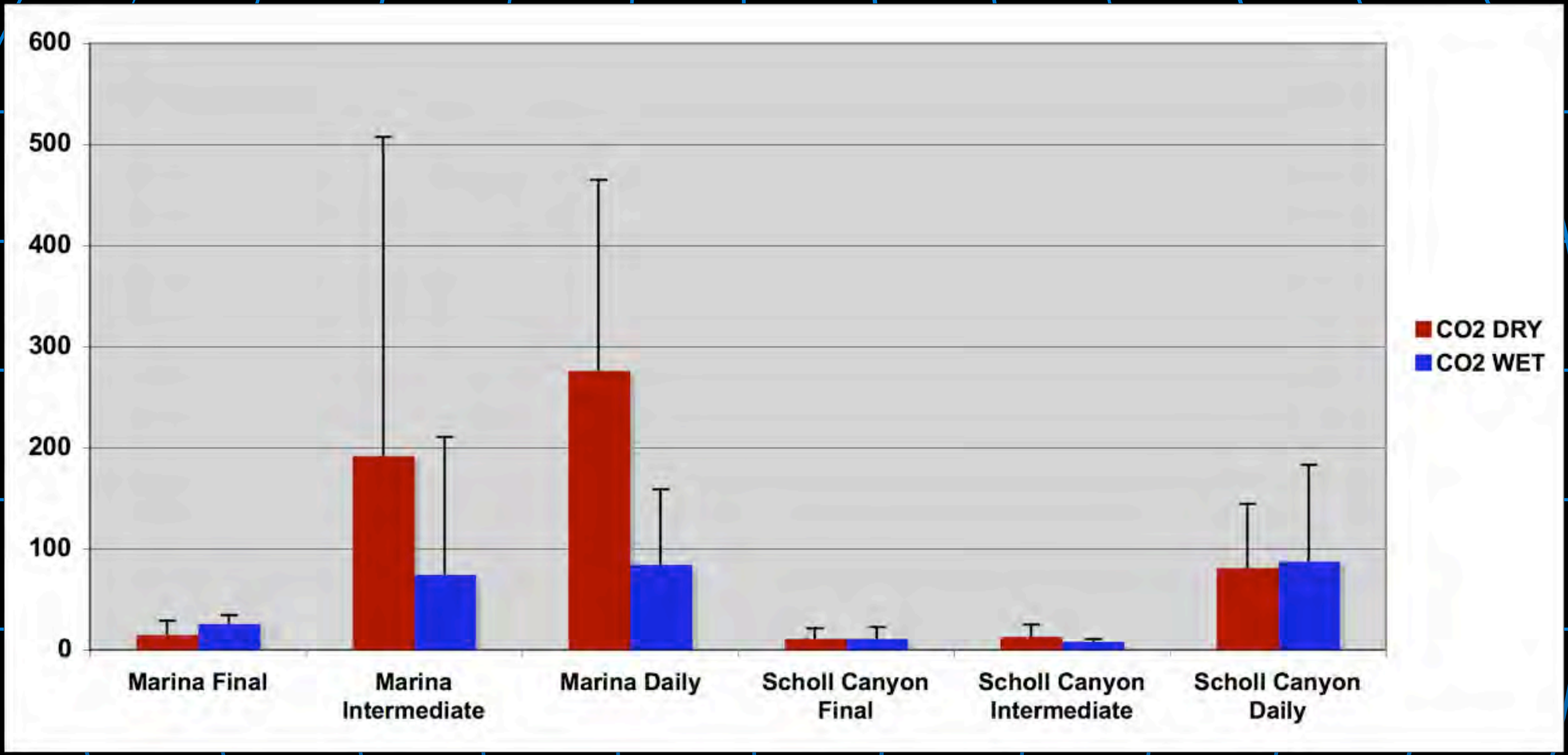
Comparison of Chamber and Probe Data

Location	Average % CH_4 oxidation	SD	Minimum	Maximum
(a) Marina: chambers	30.0	12.0	10.4	42.0
(a) Scholl Canyon: chambers	51.7	44.5	10.6	100.0
(b) Marina: probes, daily & intermediate cover (10-50 cm)	39.7	21.6	0.9	81.4
(b) Scholl: probes, final cover (30-244 cm)	47.6	9.2	39.1	73.3

chamber

probes

CO_2 emissions: soil respiration and transported landfill gas CO_2



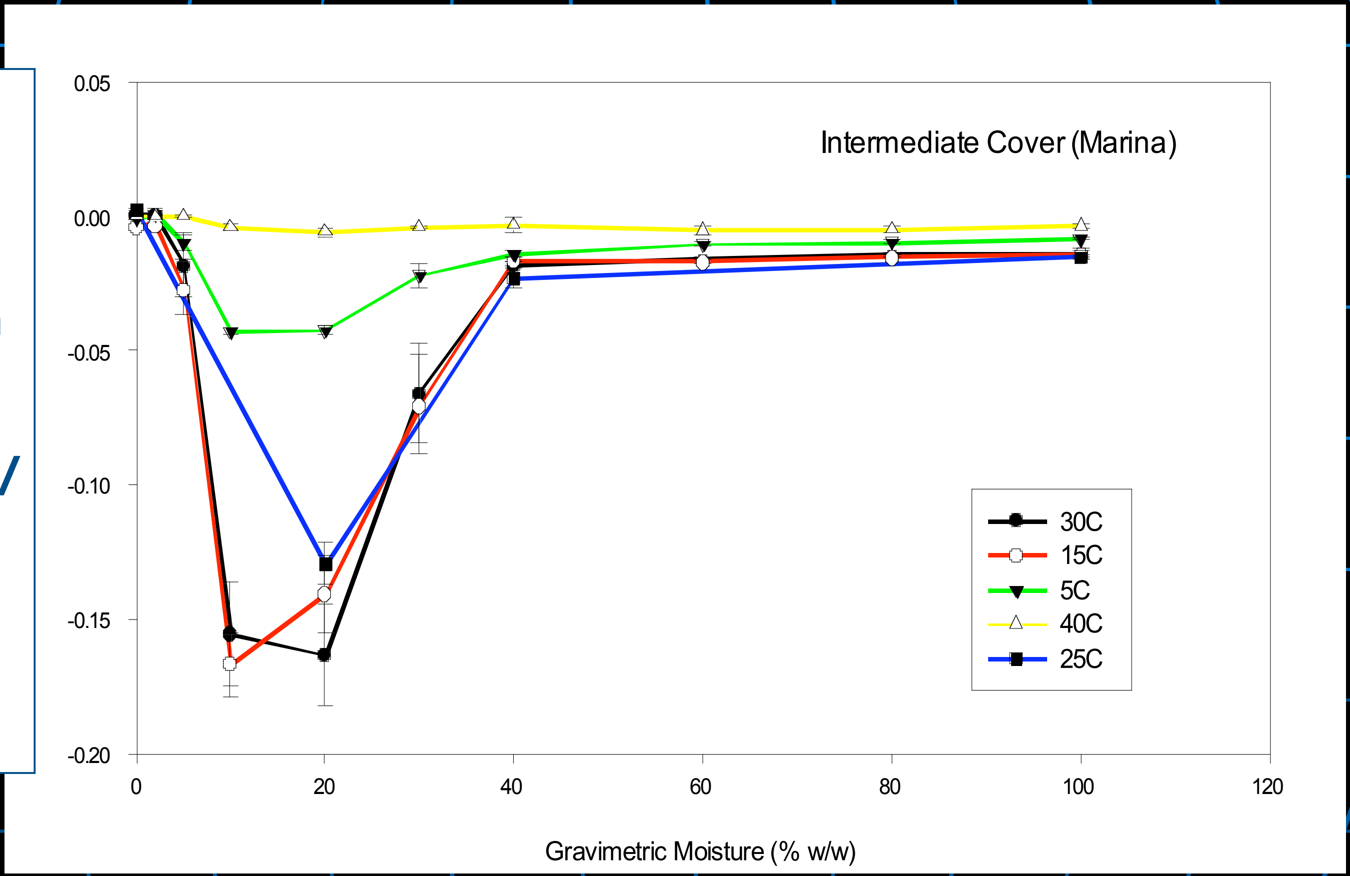
fresh refuse (no cover): 135 g m^{-2} d^{-1}
SD=117; RANGE=12.6-390

Supporting laboratory studies for modeling methane oxidation

- More than 2000 soil incubations in 6 incubators using Marina and Scholl Canyon cover soils.
- Temperature range of 0-70 deg C and moisture range of 0-100% gravimetric moisture.

Methane oxidation rates are a function of temperature and moisture (Marina data)

oxidation rate: ug CH4/ g dry soil/ day



Also, there is a minimum "threshold" moisture potential & a rate dependence on history of exposure to methane

Summary

What the CALMIM model does...

Focuses specifically on emissions, not generation: models 1-D “net” diffusional flux of methane to the atmosphere, inclusive of methane oxidation.

“Conservatively” models typical annual emissions using theoretical transport relationships and methane oxidation rates for specific cover materials, dependent on annual climatic and soil microclimate cyclicity.

Validated by field data.

Extensive laboratory studies to develop oxidation rate relationships.

Limitations of CALMIM:

Currently, 1-D diffusion only;
so does not include gaseous flux mechanisms other than diffusion (convection; ebullition; plant-mediated transport).

Models “typical” annual emissions for a cover type and area:
so does not include year-to-year deviations in emissions for that cover: appropriate for annual inventory model...

Output allows positive methane fluxes only:
so no negative fluxes...adds to conservative nature of model.

Products/Publications of this project:

- CALMIM model: freely available JAVA model for site-specific landfill methane emissions in California

- web-based user manual:in progress

- journal articles:

1. Limits and Dynamics of Methane Oxidation in Landfill Cover, Spokas, K., and Bogner, J., *Waste Management* 2010.
2. Seasonal Variability in Greenhouse Gas Emissions from Daily, Intermediate, and Final Cover Materials at Two California Landfills, Bogner, J., Spokas, K., and Chanton, J., to be submitted this week.
3. A New Field-Validated Landfill Methane Inventory Model Inclusive of Seasonal Methane Oxidation, to be submitted this month.

- conference papers (5) and presentations (7)

- final report in progress

CALMIM

CAlifornia Landfill Methane Inventory Model

(1) Site Location, Cover Materials/Area, and Gas Recovery Information (interactive template)

(2) Annual Meteorological Model:
air temperature, precipitation, solar radiation, evaporation

(3) Soil Microclimate Model:
temperature and moisture (1D)

(4) CH_4 Emission/Oxidation Model
(1D diffusion)

Annual Methane Emission Estimate for Site: for each cover & site total

Field Validation and Supporting Laboratory Studies